

Thermal Hydraulic Experimental Test Article – Report of THETA Commissioning for METL Testing

Nuclear Sciences and Engineering Division

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Thermal Hydraulic Experimental Test Article – Report of THETA Commissioning for METL Testing

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1. Executive Summary

The Thermal Hydraulic Experimental Test Article (THETA) is a facility that will be used to develop sodium components and instrumentation as well as acquire experimental data for validation of reactor thermal hydraulic and safety analysis codes. The facility will simulate nominal conditions as well as protected/unprotected loss of flow accidents in a sodium-cooled fast reactor (SFR). High fidelity distributed temperature profiles of the developed flow field will be acquired with Rayleigh backscatter based optical fiber temperature sensors. The facility is being designed in partnership with systems code experts to tailor the experiment to ensure the most relevant and highest quality data for code validation.

THETA is comprised of a traditional primary and secondary system. The primary system is submerged in the pool of sodium and consists of a pump, electrically heated core, intermediate heat exchanger, and connected piping and thermal barriers (redan). The secondary system, located outside of the sodium pool, consists of a pump, sodium to air heat exchanger, and connected piping and valves.

Figure 1 illustrates the main components of the primary system. THETA has been installed in the Mechanisms Engineering Test Loop (METL) with the primary system in the 28 inch Test Vessel #4, Figure 2 and Figure 3. Since the FY20 THETA status report, [1], further water shakedown testing was performed, some final welding modifications were performed, all system components were sanitized, dry assembled, and commissioned before installing into METL test vessel #4.

The THETA submersible electromagnetic flowmeter was welded closed to hermetically seal internal components from sodium followed by a helium leak check for the final time.

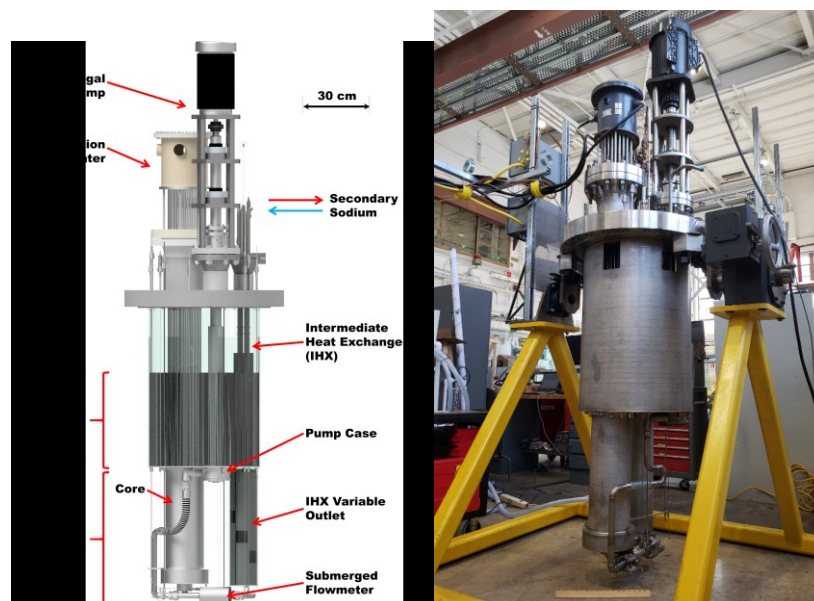


Figure 1: THETA primary system

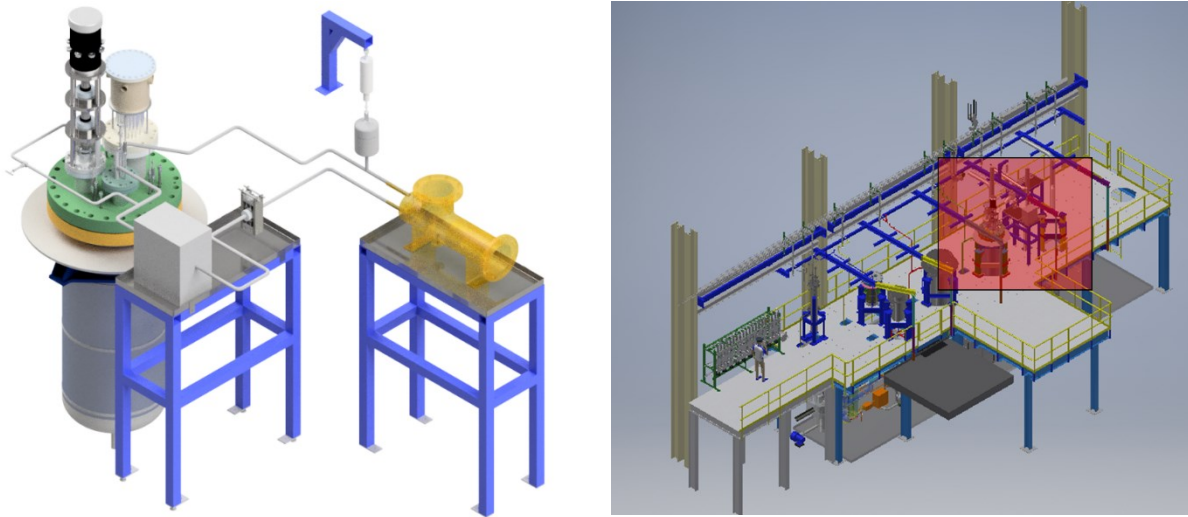


Figure 2: Isometric drawing of THETA primary vessel and secondary system left. Location of THETA in METL facility highlighted with red square, right.



Figure 3: THETA installed in METL test vessel #4

2. Introduction

The Thermal Hydraulic Experimental Test Article (THETA) is a METL vessel experiment designed for testing and validating sodium fast reactor components and phenomena. THETA has been scaled using a non-dimensional Richardson number approach to represent temperature distributions during nominal and loss of flow conditions in a sodium fast reactor (SFR), this analysis was detailed in the THETA FY19 report [2]. The facility is being constructed with versatility in mind, allowing for the installation of various immersion heaters, heat pipes, and heat exchangers without significant facility modification. THETA is being designed in collaboration with systems code experts to inform the geometry and sensor placement to acquire the highest value code validation data.

2.1. System Overview and Systems Code Application

THETA possesses all the major thermal hydraulic components of a pool type sodium cooled reactor. Figure 4 shows the piping and instrumentation diagram (P&ID) for the primary and secondary sodium circuit. A cross section of the primary vessel shows the pool and core geometry, Figure 5. As can be seen, a 28" METL test vessel is used for the primary sodium "reactor" vessel. An isometric model of the primary/secondary vessels, inter-vessel piping, and air-to-sodium heat exchanger (AHX) can be found in Figure 2.

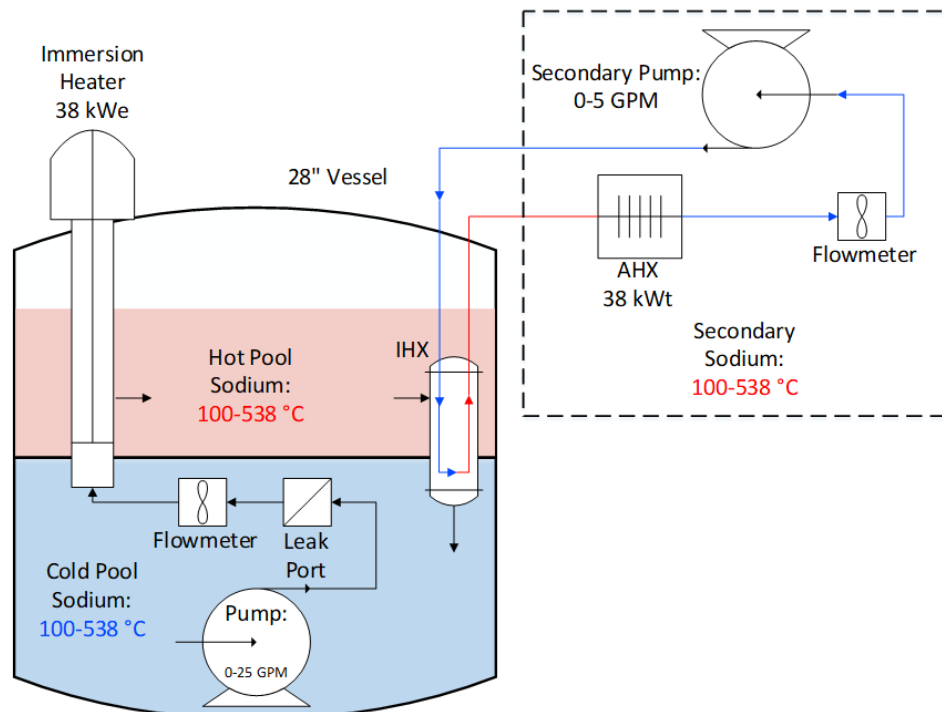


Figure 4: P&ID schematic of THETA

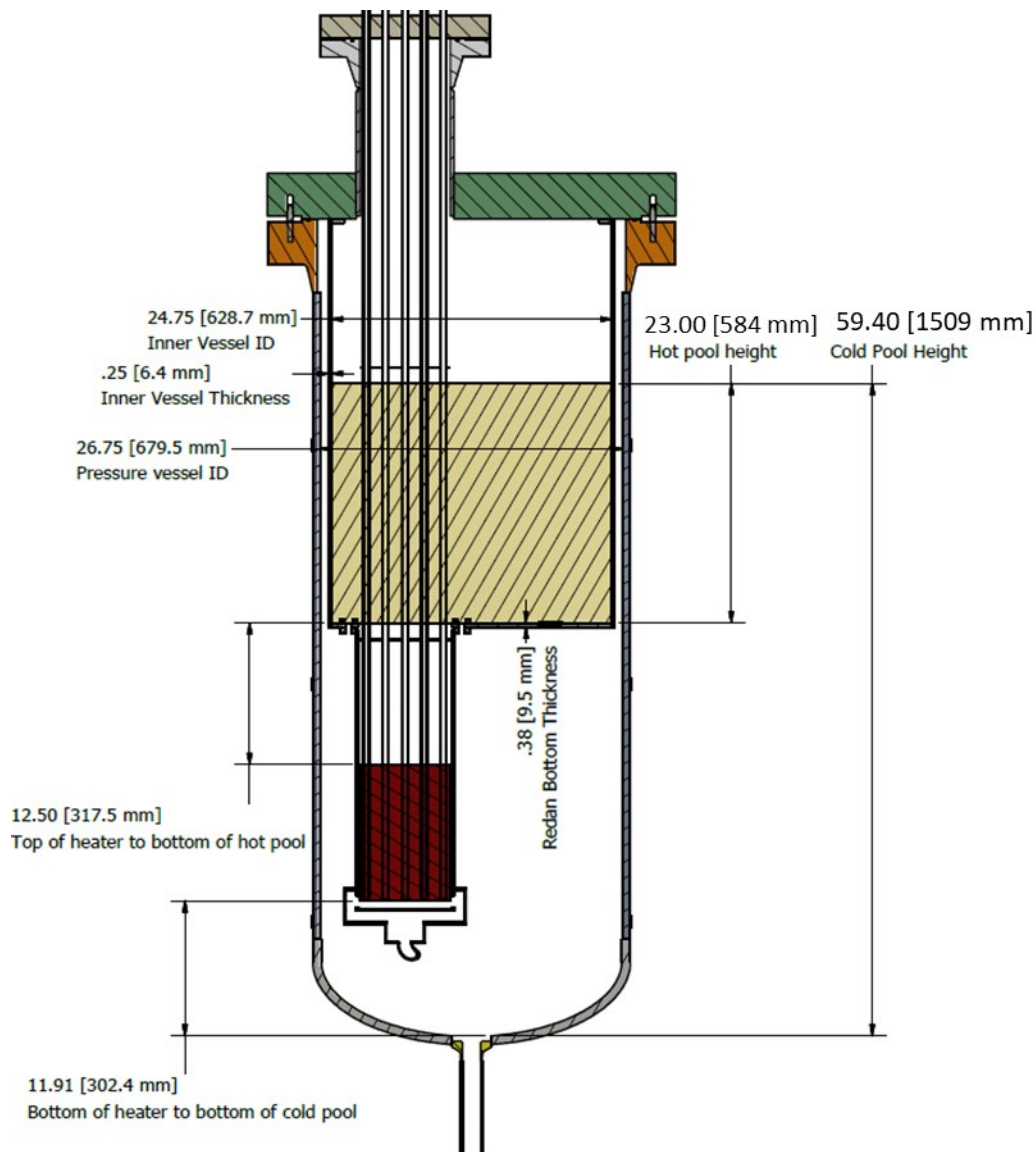


Figure 5: THETA pool and core geometry. Core nominal diameter: 0.2 [m] (8"), core heated length: 0.3 [m] (12")

Argonne National Laboratory's SAS4A/SASSYS-1 computer code is used for thermal hydraulic and safety analysis of power and flow transients in liquid metal cooled reactors. Figure 6 gives a graphic displaying the segments and compressible volumes used to perform the deterministic analysis of anticipated events such as protected/un-protected loss of flow reactor trips etc. While SAS4A/SASSYS-1 was benchmarked against tests in historic reactors, such as EBR-II [3], a modern liquid metal thermal hydraulic facility is required for further system's code validation. Please see [2] for an overview of the current systems code modeling efforts as applied to THETA.

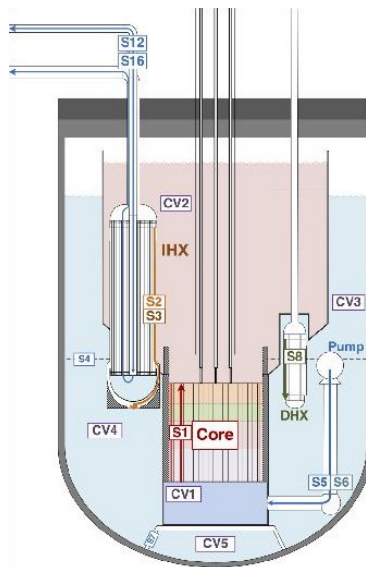


Figure 6: Schematic of SAS4A/SASSYS-1 showing locations of various compressible volumes (CV#) and segments (S#)

3. Primary Vessel Component Summary

The following section presents a summary of all primary vessel components as of March 2021 - Figure 1 provides a schematic of the primary system for reference. The primary system was tested with deionized water in FY20 and early FY21 at Argonne's building 206 [1]. The system was then transported to building 308 where the Mechanisms Engineering Test Loop (METL) is located. The system was disassembled for modifications to improve performance, as informed by the deionized water campaign. The primary system was then sanitized, rinsed and dried for final reassembly. Once reassembled, and all sensors function tested and locations documented, the system was commissioned and installed in the METL 28" test vessel #4.

3.1. Transport to METL Facility

Following the water shakedown/testing campaign the facility was partially disassembled to facilitate transport from the water testing facility in Argonne building 206, to the METL facility in Argonne building 308. Figure 7 provides a photo of THETA after removal from polycarbonate vessel following water testing. Figure 8 and Figure 9 show images of THETA being transported on the yellow test article A-frame mount with the use of a fork truck and tractor/trailer. All of the electrical enclosures and auxiliary equipment were disconnected from power and placed on pallets to facilitate their move to the METL facility, Figure 10.



Figure 7: THETA assembly immediately following removal from 260 gallon polycarbonate vessel used for deionized water testing in Argonne building 206



Figure 8: THETA primary flange and inner vessel being picked up from building 206 loading dock



Figure 9: THETA primary flange and inner vessel being placed on trailer for transport to METL facility



Figure 10: Electrical enclosures, pump motor, thermocouples, and sensors prepared for riggers to transport from building 206 water testing facility to building 308 hibay for installation at METL

3.2. Secondary Dip Tube Installation

Once THETA arrived at the METL facility, the test article was disassembled to facilitate final welding modifications as well as a thorough sanitization. Figure 11 shows the inner vessel being removed to expose the underside of the flange to allow for installation of the secondary system dip tube.

Figure 12 shows the mounting fixture for the THETA secondary system dip tube being welded into position. The mount possesses a 3/4" Swagelok compression tube fitting whereby a 3/4" stainless steel dip tube may be fixed, Figure 13. The dip tube sodium is transported through the

THETA flange to the secondary system fill valve, Figure 14. This fill valve is a Swagelok welded bellows valve. All welds above the flange, where sodium-atmosphere leaks could occur, were radiographed in the shop, where possible. Field welds on the secondary system will be radiographed once the secondary system is attached to THETA, before filling with sodium, bringing the secondary system to 100% radiographed welds prior to filling. Helium leak check will also be performed in the field with a mass spectrometer leak detector before charging with sodium as the final non-destructive test of the system. The dip tube can be seen installed in the system in Figure 15.



Figure 11: THETA being disassembled in building 308 for final modifications and sanitization before reassembly



Figure 12: Welding secondary system dip tube connection. Argon purge to purify full penetration weld provided by plastic tube, left. Final welded dip tube connection with 3/4" Swagelok connection for attachment of 3/4" stainless steel dip tube.

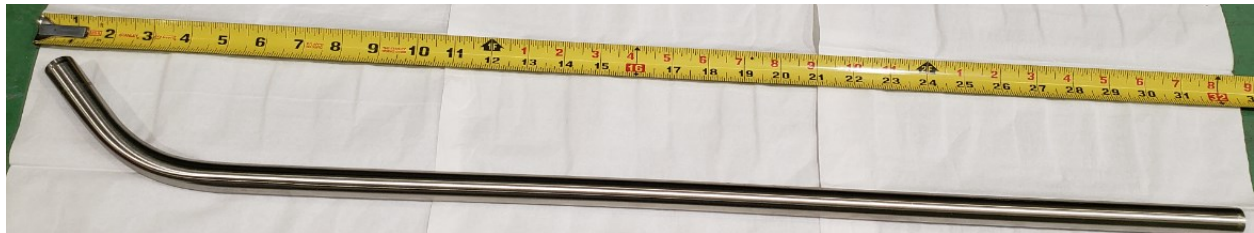


Figure 13: 3/4" stainless steel dip tube

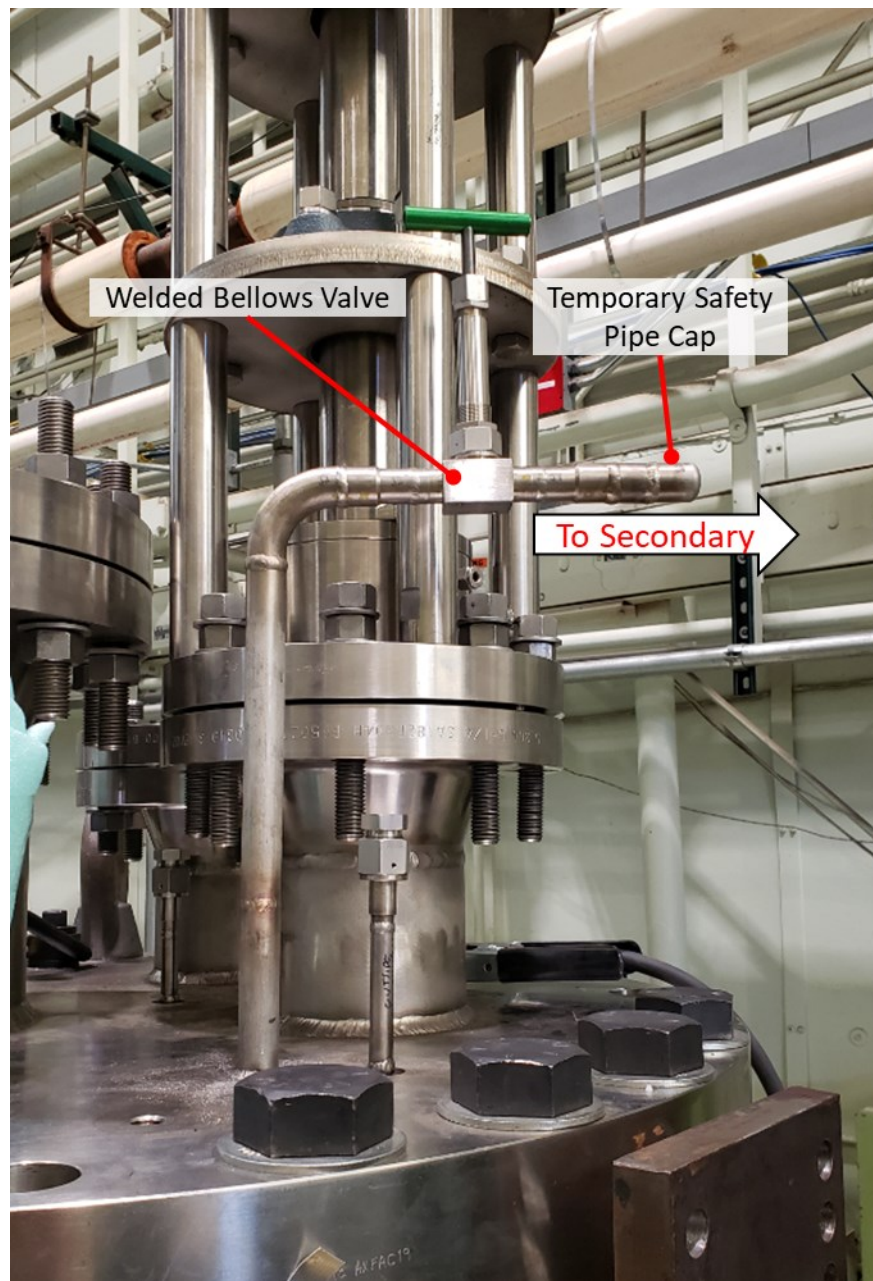


Figure 14: Final welded secondary system transfer valve on top of the primary system flange. This facilitates transfer of METL sodium from THETA primary system into secondary system with the use of a dip tube, eliminating the need to use a second METL vessel or an auxiliary supply of sodium that would require additional sodium purification infrastructure.

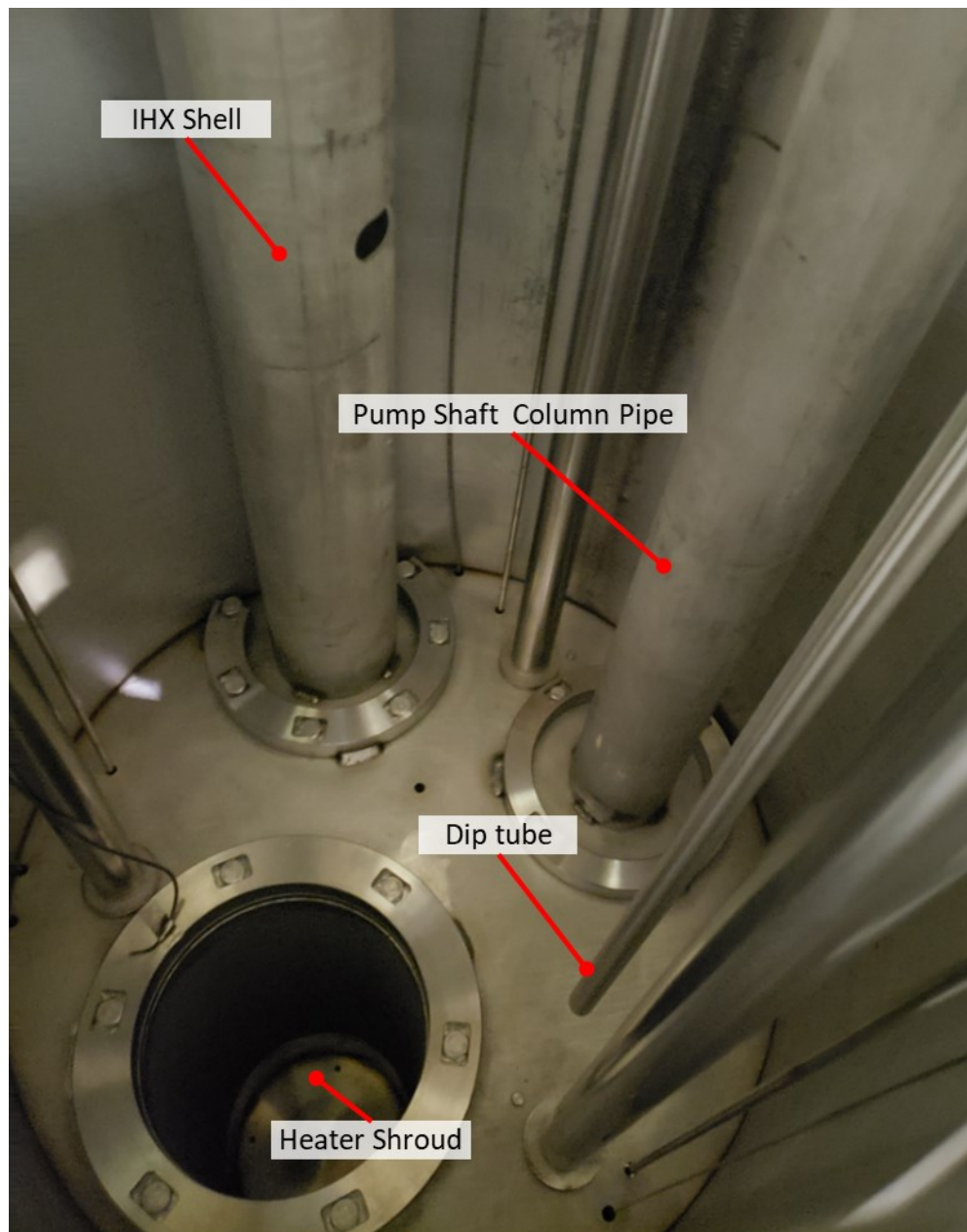


Figure 15: Picture of inner vessel hot pool before installation of immersion heater

3.1.Pump

As mentioned in [1] the THETA primary pump impeller was 3D printed in 316 stainless steel. Final machining was performed on the impeller to expand the undersized bore to the correct clearance to mate with the pump shaft (3D printed tolerances were not sufficiently tight so the bore was purposely undersized to facilitate conventional machining). In addition, all of the surfaces were passed over with the mill to remove the minimum required material to bring all surfaces parallel to a single datum plane. This ensures balanced operation without vibration.



Figure 16: 3D printed THETA 4.5" diameter primary impeller during final conventional machining to bring purposely undersized bore to spec and flatten out all surfaces to ensure balanced operation. This is during machining; the final passes of the mill were finer to produce a smoother finish.

During water testing, water was seen escaping the top of the pump column pipe due to pressure in the pump case building up and leaking through the labyrinth seal, seal described in [1]. Figure 17 shows a photo of the water escaping the top of the column pipe at around 1,150 RPM (water flowrate of 11.4 GPM). Figure 18 shows the pump speed vs flowrate relevant to this testing.

In order to enhance the performance of the pump, the column pipe inner diameter was enlarged from 3.26 to 4.26" and length was extended by 4" at the top with the use of a welded on expansion piece, Figure 19. This effectively provides more volume for the sodium at the top of the column pipe to reside before leaking into the hot pool sodium. As can be seen, there is an 1/8" Swagelok compression fitting at the very top of the expansion piece to mount a thermocouple probe. This allows for determination of maximum pump speed before sodium begins to leak out of the top of the column pipe as a discrete rise in temperature will be seen when the high thermal conductivity sodium touches the thermocouple. Figure 20 provides a photo of this thermocouple as installed.

A vibration sensor (IFM Efector Inc, PN UW0006) was added to the pump motor to determine resonant frequencies of the pump shaft as the speed of the shaft was increased from 0-1800+ RPM in water at room temperature. The vibration sensor location was highlighted in Figure 17 and vibration sensor data provided in Figure 21. As can be seen there is a resonant frequency at 1050 RPM as well as at 1.5x this speed at 1600 RPM. It is best not to operate at these particular speeds

as the shaft vibration could cause premature wear of the graphite seal, rubbing of the labyrinth seal and signal noise in the sensitive optical fiber instrumentation.



Figure 17: Photo showing the vibration sensor installed on the primary pump motor, left, as well as water escaping the top of the column pipe, right.

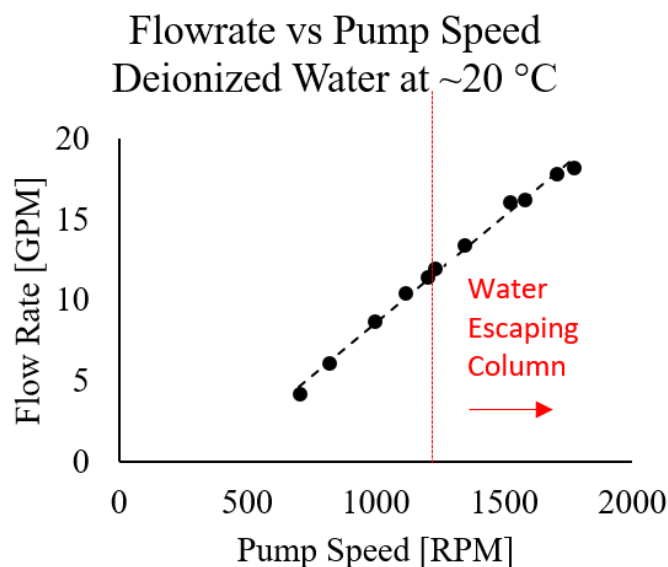


Figure 18: Water began escaping column pipe, Figure 17, at a speed of 1,150 RPM (flowrate of 11.4 GPM). At 1,100 RPM (11 GPM) there was not water escaping.

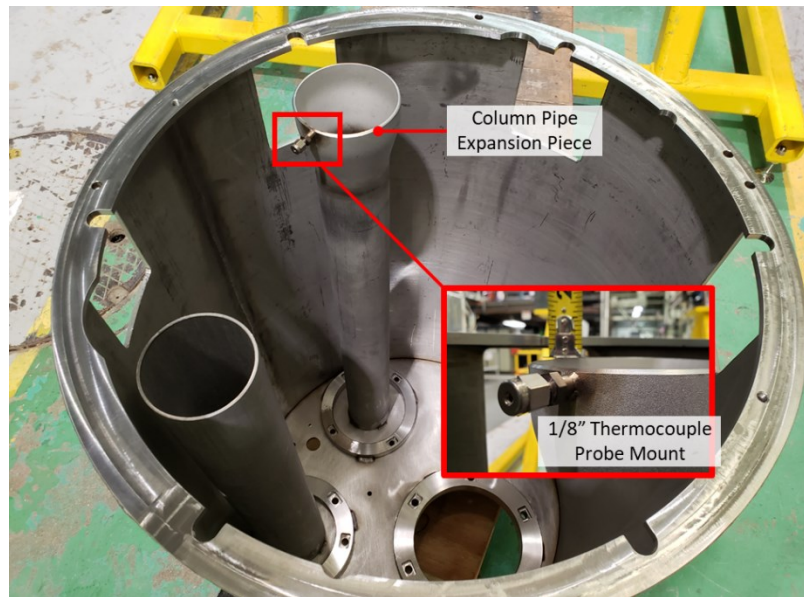


Figure 19: Column pipe expansion piece shown with 1/8" thermocouple probe mount location highlighted. A thermocouple is installed at this location to determine maximum pump performance, before sodium begins to flow out of the top of the column pipe due to high pump case pressure



Figure 20: Photo of the 1/8" thermocouple probe mounted to the top of the column pipe to facilitate determination of maximum pump speed before sodium is pushed to the top of the column.

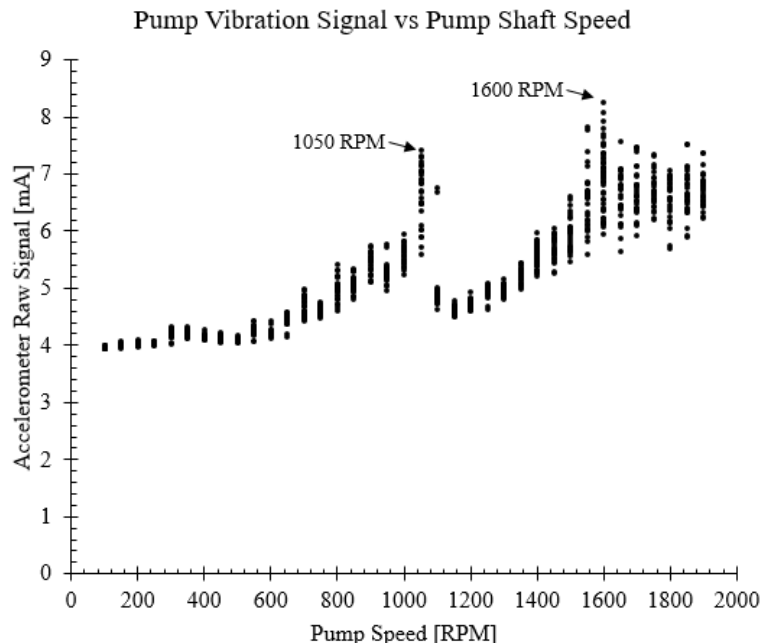


Figure 21: Pump motor vibration as a function of motor speed. Pump operating in water at room temperature. Resonant frequencies seen at accelerometer peaks at 1050 RPM and 1600 RPM

After water testing and transport from building 206 to building 308, the pump was disassembled and sanitized with a 1% dilution ratio of Alconox 1125 (a non-halogen based, gentle detergent) and deionized water wash followed by a deionized water rinse, Figure 22. A very small amount of graphite seal debris was seen in the debris well, Figure 23, after the extensive water testing campaign. There was no other evidence of graphite in the system, thus the graphite thrower and debris well are performing as designed, [1], [2].

After cleaning, the pump was reassembled and runout at the bottom of the pump shaft where the pump impeller is mounted was measured with a dial indicator. A reading of $\pm 0.005''$ was measured, this is within acceptable specification, Figure 24.

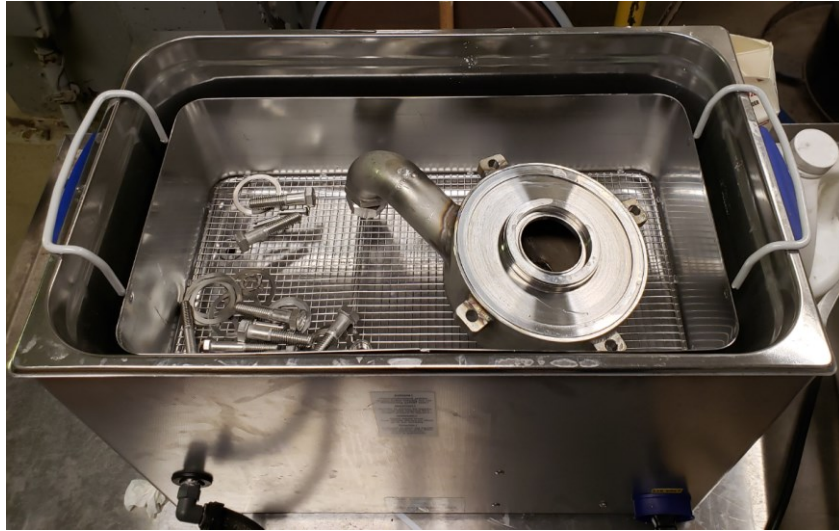


Figure 22: Pump components in ultrasonic bath for final cleaning

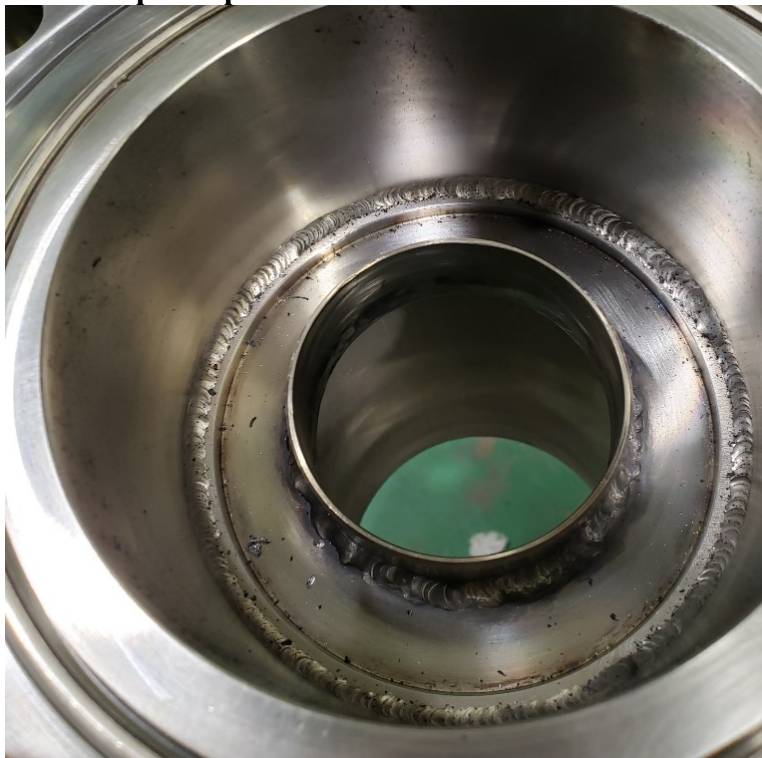


Figure 23: Pump debris well after water testing campaign. No graphite debris was evident below the debris well. A complete description of debris well can be found in [1], [2]



Figure 24: Dial indicator on bottom of pump shaft where impeller is mounted showed acceptable shaft runout of ± 0.005 " before final assembly.

3.2.Primary System Assembly

The primary system components were sanitized with the use of a 1% dilution ratio of Alconox 1125 (a non-halogen based, gentle detergent) and deionized water wash followed by a thorough rinse of deionized water. Figure 25 shows the inside of the inner vessel after cleaning. Figure 26 and Figure 27 shows the cold pool system components and sensors assembled, following cleaning. Components were determined clean when after a lint free laboratory wipe was passed across its surface there was no visible contamination on the wipe.

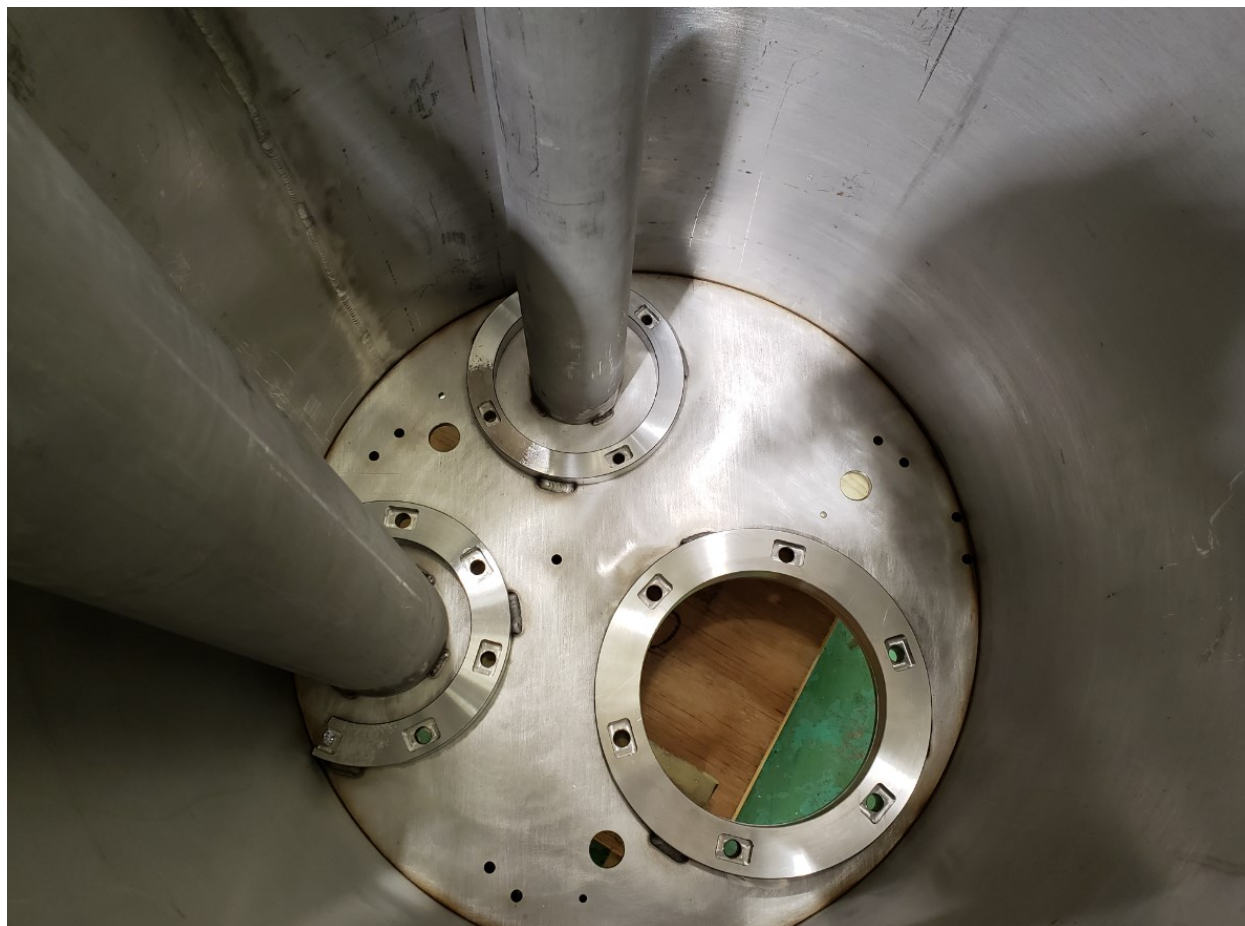


Figure 25: Inner vessel following final cleaning

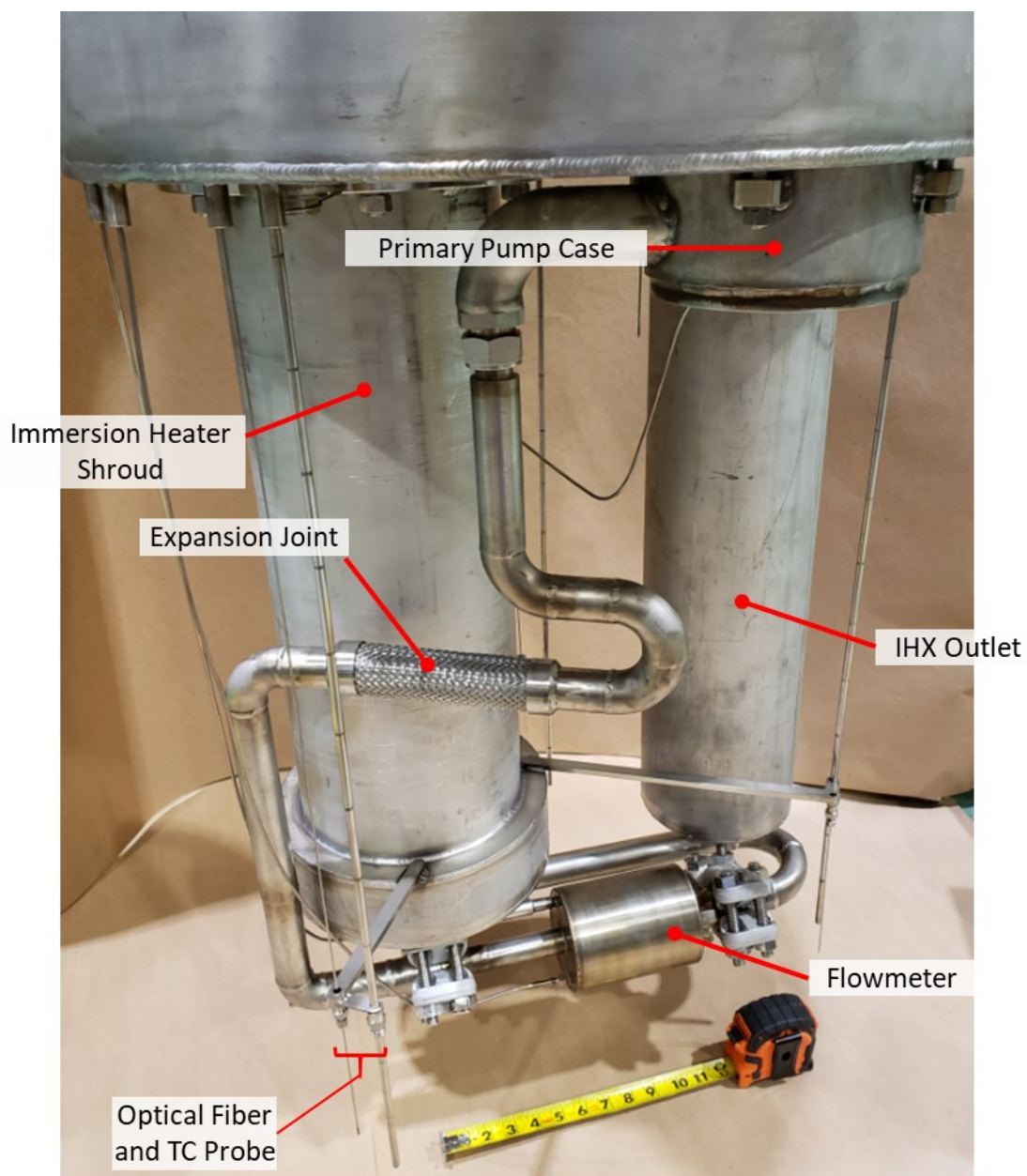


Figure 26: THETA primary piping

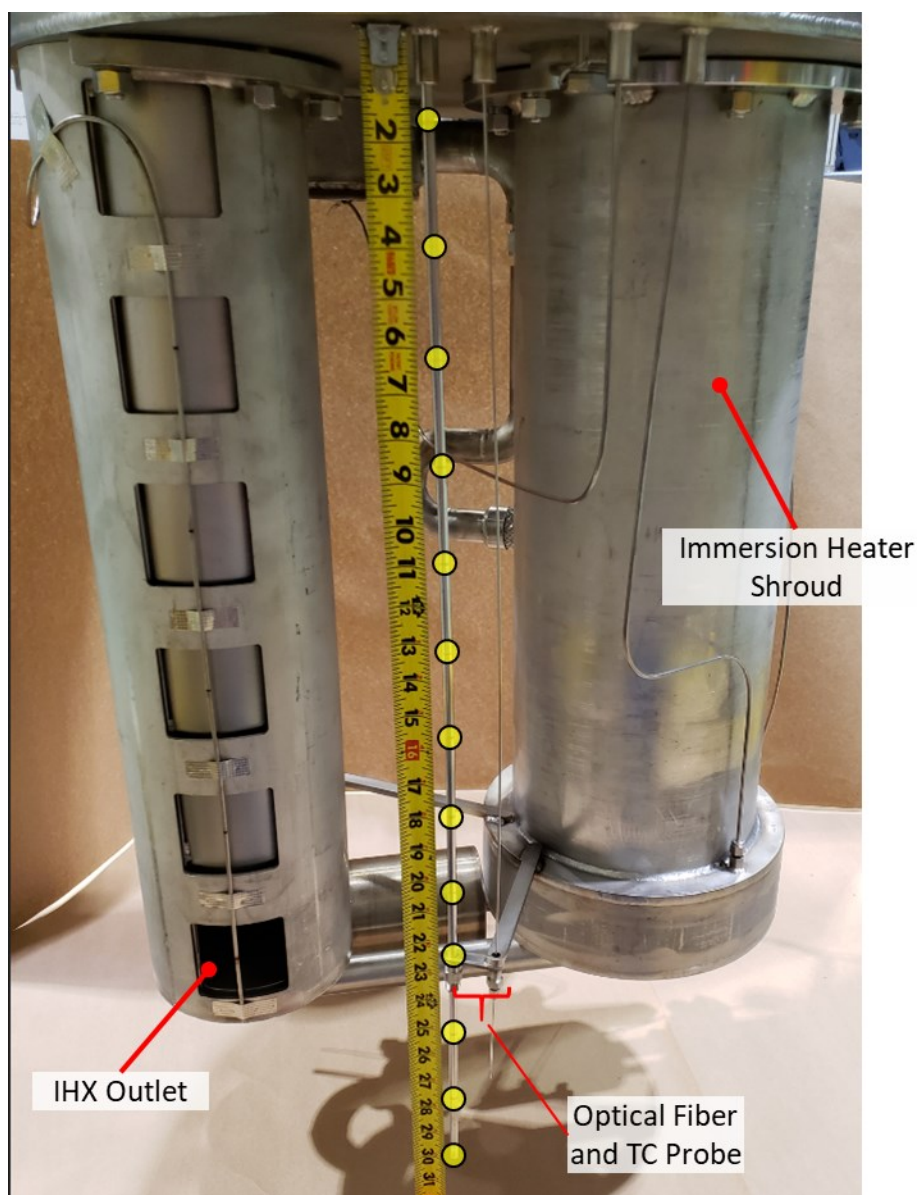


Figure 27: Photo showing various features of the THETA cold pool. Note that the 13 junctions on one of the QTY (3) thermocouple rakes have been highlighted with yellow circles.

3.3. Instrumentation

Table 1 summarizes THETA instrumentation which includes single and multi-point thermocouples, distributed optical fiber temperature sensors, level sensor, and flowmeter voltage measurements. The port locations on the top flange have been labeled in Figure 28. Notice that Ports 1, 5, and 12 have all been expanded four-fold to ports 1a, 1b, 1c, 1d, etc. This was achieved with the use of a custom fabricated adapter that mates a Conax connector with QTY (4) 0.125" feedthroughs with the existing 1/2" Swagelok VCR fitting, Figure 29.

Table 1: THETA instrumentation and measurement. Port positions provided in Figure 28

Port	Instrument	Measurement
1a	Single TC	Pump inlet temperature
1b	Single TC	Core inlet temperature
1c	Blank	-
1d	Blank	-
2	Single TC	Core outlet temperature
3	Fiber	Hot and cold pool distributed axial temperature
4	Rake TC	Hot and cold pool distributed axial temperature
5a	Rake TC	IHX outlet and inner vessel near wall temperature
5b	Single TC	Pump shaft column overflow temperature
5c	Blank	-
5d	Blank	-
6	Rake TC	Hot and cold pool distributed axial temperature
7	Fiber	Hot and cold pool distributed axial temperature
8	Rake TC	Inner vessel near wall temperature in cold pool
9	Rake TC	Hot and cold pool distributed axial temperature
10	Fiber	Hot and cold pool distributed axial temperature
11	Level Sensor	Sodium hot pool at 23" in elevation
12a	MI Cable	Flowmeter voltage
12b	Single TC	Flowmeter temperature
12c	Blank	-
12d	Blank	-
13	Fiber	Hot and cold pool distributed axial temperature
14	Fiber	IHX distributed axial temperature
15	Rake TC	IHX distributed axial temperature
16-20	Single TCs	Core temperature 3" above bottom of elements

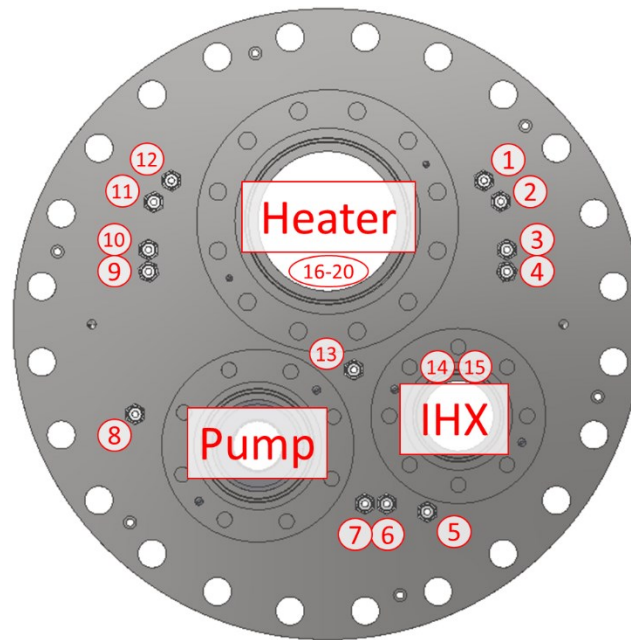


Figure 28: THETA instrumentation port locations



Figure 29: Instrumentation adapter 1/2" Swagelok VCR fitting (right side) to Conax Compression Seal fitting with graphite sealant (left side) to accommodate QTY (4) 1/8" diameter sensors

The IHX outlet temperature thermocouple rake that acquires IHX outlet temperatures at each of the 6 elevations was mounted with the use of a capacitive discharge spot welder. As can be seen in Figure 30, 0.008" thick 316 stainless steel sheet metal was used to fix the thermocouple probe to the IHX outlet assembly by spot welding the sheet metal tight on either side of the probe.

The same spot welding process was used to mount the thermocouple rake that acquires near wall temperatures of the inner vessel in the cold pool, Figure 30.

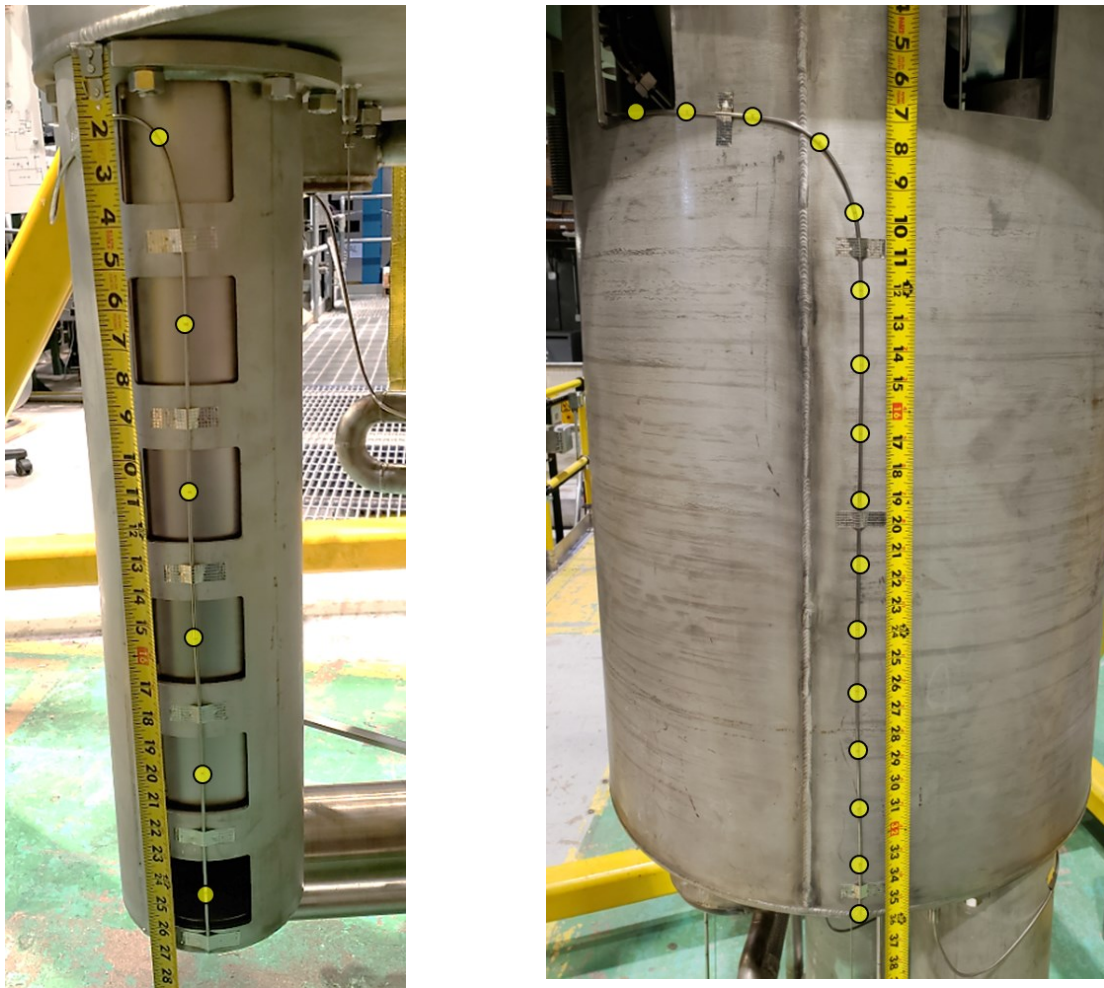


Figure 30: LEFT: intermediate heat exchanger outlet showing 1/8" multijunction thermocouple probe with junctions at the center of each of the 6 outlets. 0.008" thick 316 stainless steel sheet metal was used to fix the position of the probe. QTY (6) thermocouple junction locations were highlighted with yellow circles for clarity. RIGHT: Temperature is read on the outer surface of the inner vessel with the use of a 1/8" multijunction thermocouple probe. QTY (16) thermocouple junction locations were highlighted with yellow circles for clarity.

The THETA submersible electromagnetic flowmeter was mounted in primary loop circuit, the signal and thermocouple feed through wires were fed out of the sodium and vapor space through ports 12a and 12b, respectively, Figure 31.

A custom-built single point electrical continuity level detector was installed in port 11 to allow for precise level determination, Figure 32. The level sensor is set to signal full when the hot pool level is at an elevation of 23" above the bottom of the inside of the inner vessel.

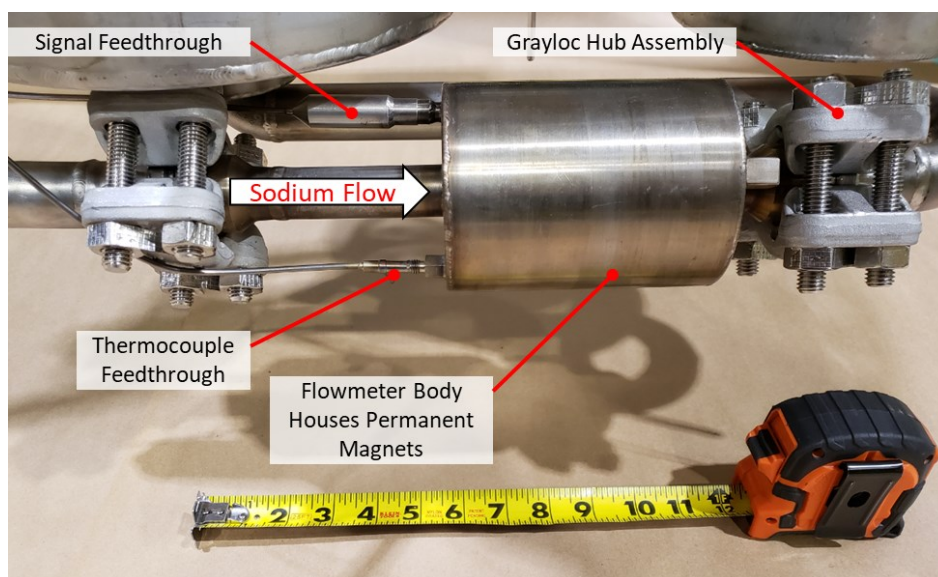


Figure 31: Electromagnetic flowmeter installed in THETA primary piping. All 316 stainless steel Grayloc assemblies with Inconel uncoated seal rings are used.

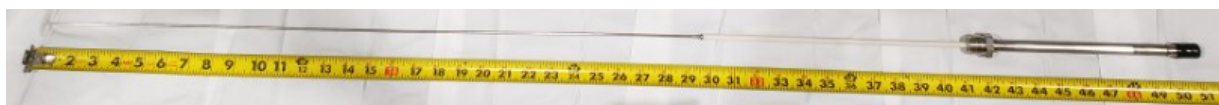


Figure 32: Custom built single point continuity level detector. All stainless steel and alumina construction. BNC connector for sensor reading.

3.4. Submersible Flowmeter

A submersible permanent magnet flowmeter has been designed to acquire primary sodium flowrate, Figure 31. The flowmeter uses a magnetic field generated by high temperature Samarium-Cobalt (SmCo) magnets, oriented perpendicular to sodium flow, to generate a Lorentz current that is linearly proportional to flow. A complete description of the design and construction of the flowmeter can be found in [1], [2].

The submersible flowmeter sensor wires were exposed during calibration in an auxiliary sodium loop to allow for modification if necessary. The flowmeter was then brought to a vendor where the flowmeter was hermetically sealed with the use of precise TIG welding under a microscope. As can be seen in Figure 33, the signal wires were welded to the MI cable feedthrough. A small rectangular piece of 0.030” thick alumina electrical insulator (insulator #2 in Figure 33) was then installed to separate the signal wires. A tube shaped electrical insulator was then slid over the sensor wires (insulator #1), followed by the signal wire shroud. The shroud was then micro welded to the flowmeter body and the MI cable feedthrough to provide a completely hermetic seal.

In order to pull vacuum and backfill with a cover gas, a backfill port is present on the thermocouple feedthrough, Figure 34. A vacuum was pulled with the turbo pump on the helium leak detector to evacuate any contaminant gasses in the flowmeter to a pressure of <1 milliTorr. A wand was then used to pass helium across all surfaces of flowmeter. A helium leak rate of $<10^{-8}$ atm-cc/sec was seen during this operation, a satisfactory result, Figure 35 and Figure 36. The flowmeter cavity was then backfilled to a helium pressure of 23 inH₂O (0.83 PSIG). This will yield an internal helium cavity pressure of 13 PSIG at 250 °C and 26 PSIG at 500 °C. The vacuum/helium backfill port was then crimped shut and immediately TIG welded to hermetically seal the cavity Figure 34. A photo of the complete flowmeter ready for installation can be seen in Figure 37.

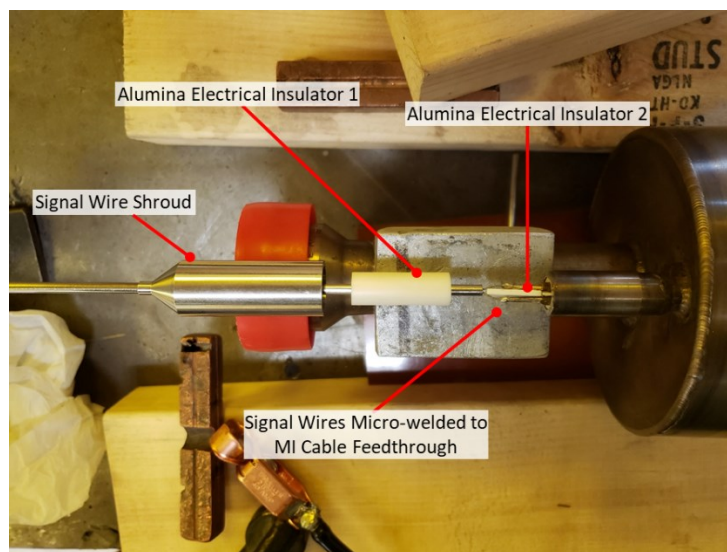


Figure 33: Sealing off signal wire feedthrough on THETA primary flowmeter.

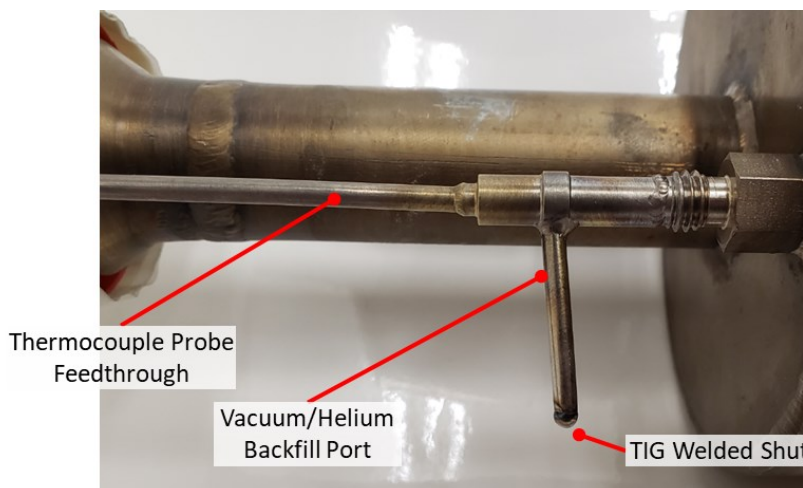


Figure 34: Vacuum/helium backfill port TIG welded shut

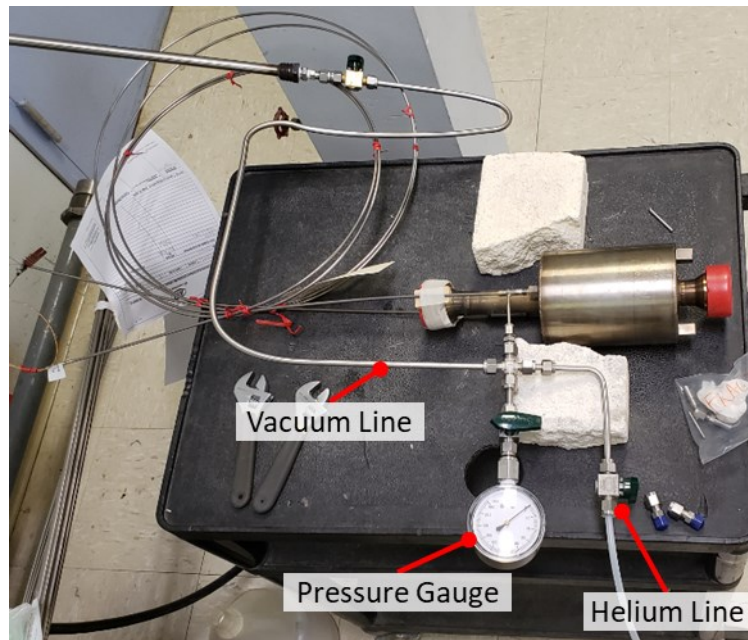


Figure 35: Setup to facilitate pulling vacuum and backfilling flowmeter cavity with helium.

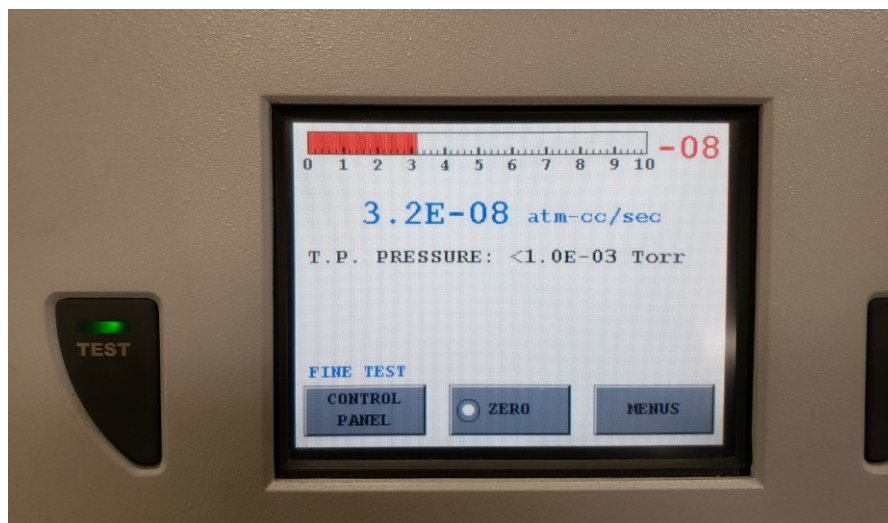


Figure 36: Helium leak detector showing hard vacuum of <1 milliTorr pulled on assembly and a helium presence of $<10^{-8}$ atm-cc/sec in the internal cavity of the flowmeter where signal wires, thermocouple and magnets reside. Helium gas was passed across all surfaces of the flowmeter.

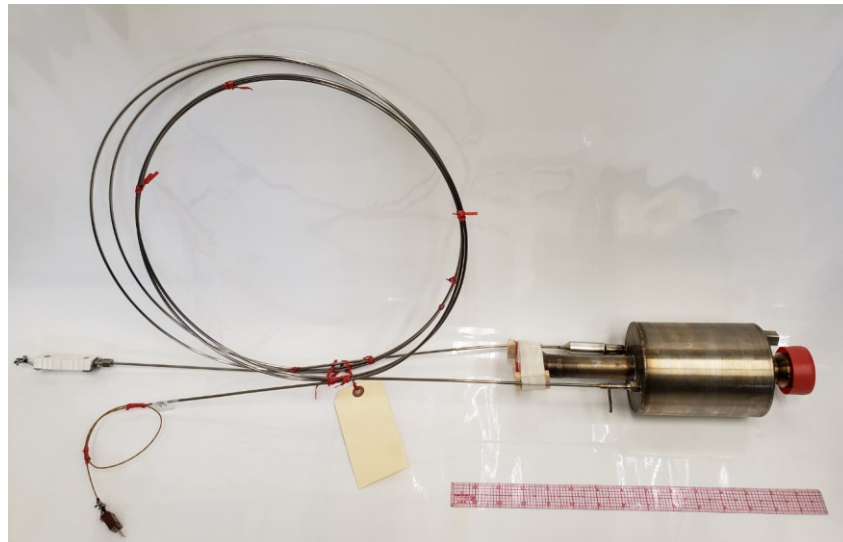


Figure 37: Photo of completed THETA submersible electromagnetic flowmeter with 15" ruler for reference. Note the 1/8" MI cables transmitting temperature and sensor data have been spooled up for easy transport

3.5. Installation of Primary Assembly

Following final sanitization and assembly of the primary assembly, THETA was transported to METL 28" vessel #4 with the use of the 5 ton overhead crane in the building 308 hibay, Figure 38 and Figure 39. THETA as installed in the vessel can be seen in Figure 3.



Figure 38: Installation of THETA into METL with building 308 overhead crane

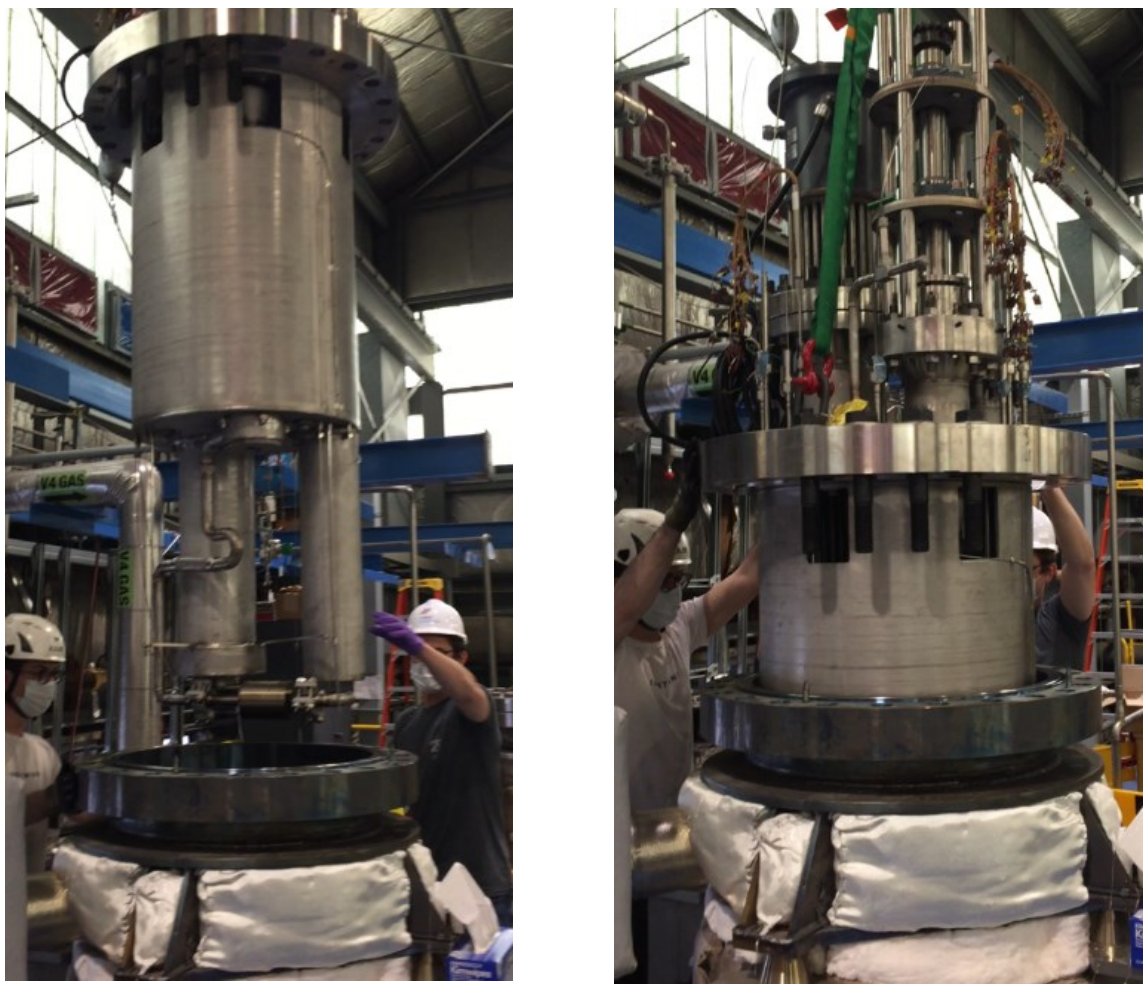


Figure 39: Installation of THETA into METL with building 308 overhead crane

Finally, a majority of the electrical control and data acquisition cabinets for THETA were installed on the North side of the METL mezzanine, Figure 40.

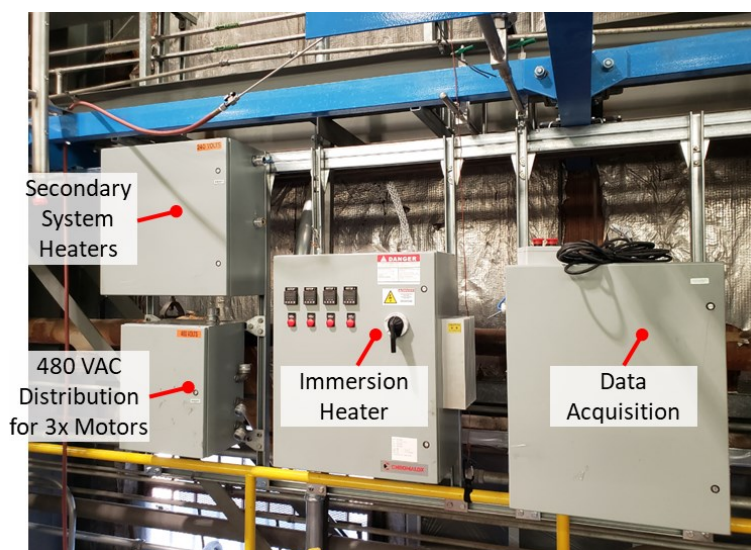


Figure 40: THETA electrical control cabinets installed on METL mezzanine, north wall

3.6. METL 28” Flange Fastener Improvement

Significant galling was seen in previous testing when pairing 304 stainless steel nuts with 304 stainless steel bolts to mount a blank 28” flange to the METL vessel at a temperature of $\sim 500^{\circ}\text{C}$, even with the use of nuclear grade nickel based high temperature anti-seize. 1-1/2”-12 heavy hex nuts in Inconel 718, SB-637 with silver coating were acquired to mate with 304 stainless steel bolts to seal the THETA flange to the 28” METL vessel flange, Figure 41. The use of dissimilar metals and the interstitial silver plating should provide superior galling resistance.

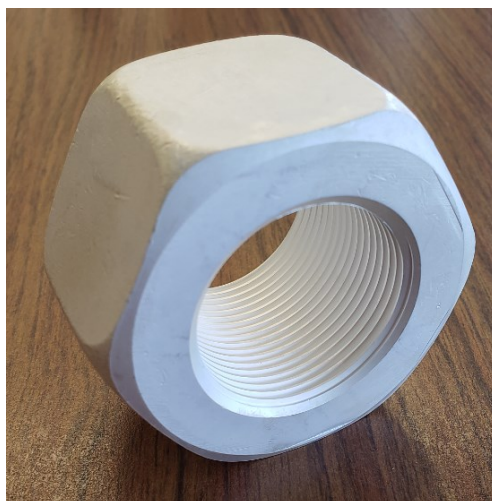


Figure 41: Significant galling was seen when pairing 304 stainless steel nuts with 304 stainless steel bolts to mount the THETA flange to the METL vessel, even with the use of nuclear grade high temperature anti-seize. 1-1/2”-12 heavy hex nuts in Inconel 718, SB-637 with silver coating were acquired to mate with the stainless steel flange bolts

4. THETA Model Development

Modeling of the Thermal Hydraulic Experimental Test Article (THETA) experiment has been performed using the SAS4A/SASSYS-1 fast reactor safety analysis code. A THETA model has been developed to represent the THETA experiment design developed at Argonne to demonstrate the importance of key elevations on natural circulation flow rates. The model currently includes the core channel and the primary heat transport system of the THETA experimental facility. A summary of this work can be found in [2].

5. Conclusions and Path Forward

THETA has completed the commissioning phase of its development for insertion into METL. All major components of the primary system have been installed in METL vessel #4. The path forward will include connecting all data acquisition and control systems, wiring the immersion heater and pump, followed by shakedown testing of the pump in the dry, room temperature vessel. Note: immersion heater will remain off for all dry testing to prevent overheating. Once systems are performing in a satisfactory manner, the vessel will be brought to a temperature of 200 °C with the use of the vessel heaters for high temperature testing of the pump and other sensors. Then, finally, sodium at a temperature of 200 °C will fill THETA and shakedown testing in sodium will commence followed by THETA planned experimental campaign for the primary system.

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7. References

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- [2] M. Weathered *et al.*, “Thermal Hydraulic Experimental Test Article – Status Report for FY2019 Rev. 1,” Lemont, 2019.
- [3] T. Sumner and A. Moiseyev, “Simulations of the EBR-II Tests SHRT-17 and SHRT-45R,” in *16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16)*, 2015.



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